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Using the Whole-Building Design Approach to Incorporate Daylighting into a Retail Space

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Using the Whole-Building Design Approach to Incorporate Daylighting into a Retail Space

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ABSTRACT

Daylighting is the most important element in creating a low-energy building in many climates. Reducing lighting loads decreases the electrical energy required for operating lighting systems and reduces building cooling loads. However, many commercial building owners are skeptical about daylighting strategies because of the perceived risk associated with what is considered a "new" concept. Also, architects and engineers find it difficult to optimize the daylighting system so as to minimize the sum of heating, cooling, lighting, and ventilation energy costs, and to control glare. This reluctance is especially true in the retail-building sector where "bright" lighting is equated to meeting product sales goals.

This paper described using the whole-building design approach to implement daylighting and other strategies into the BigHorn Center, a collection of home improvement retail spaces in Silverthorne, Colorado. The complex was constructed in three phases. Daylighting was an integral part of the design of the Phase III building. Energy consultants optimized the daylighting design through detailed modeling using an hourly building energy simulation tool

Substantially reducing the electric lighting load minimized the cooling loads, which could then be completely met with natural ventilation. Other strategies included optimized envelope features, radiant slab heating, and optimized building controls. This paper focuses on the daylighting design of the Phase III building and summarizes the findings from the building envelope and systems design analyses.

Introduction

The retail sector in the U.S. has been slow to adopt sustainable building practices for a variety of reasons (where sustainability means providing for the needs of the present without detracting from the ability to fulfil the needs of the future (UNCED 1992)). These reasons include a desire to construct retail spaces quickly (allowing little time to design the building) and the uncertainty of how nontraditional building envelopes and systems will affect sales. Retailers have significant experience in controlling lighting levels and other environmental elements to ensure that stores remain profitable. Due to the risk of reduced profits, most retailers are reluctant to incorporate solar features, including daylighting and passive techniques, into the building design.

A remarkably different approach was taken in the design of the BigHorn Center in Silverthorne, Colorado. One of the retailer's primary goals was to minimize the environmental impact of the new building. As a result, the design team applied the whole-building design approach and successfully integrated solar and energy efficient technologies into the building design (Torcellini, Hayter & Judkoff 1999).

From the beginning, a design goal for the BigHorn Center was to create a sustainable retail environment. Even before the complex was completed, the owner attributed increased sales in his existing facility to the publicity received for his efforts towards sustainable design of the BigHorn Center.

The BigHorn Center consists of five retail spaces constructed in three phases. Phase I, completed in February 1998, consisted of the site preparation and construction of the first building, now occupied by a major catalogue retailer. The Phase I building design includes a super-insulated envelope, daylighting, advanced lighting technologies, and other energy-efficient features. The Phase II building was completed in March 1999 and contains two home improvement specialty stores. In addition to the energy-efficient envelope and systems similar to the Phase I design, Phase II includes a 2-kW building-integrated photovoltaic (PV) system. This grid-tied PV system laminated onto standing-seam metal roof panels was installed to offset building electrical loads.

Phase III, completed in April 2000, houses a hardware store with an associated building materials warehouse (Figure 1). This phase incorporates the most aggressive sustainable design strategies of the three phases. Improvements based on lessons learned in Phases I and II are part of the Phase III design. These strategies include daylighting, advanced lighting technologies, natural ventilation cooling, transpired solar collector, building-integrated PV, improved envelope features, and integrated controls. This paper describes the Phase III building.

Figure 1. Phase III Front Façade (East Elevation)

The BigHorn Center is one of the first examples in the U.S. of integrated daylighting and natural ventilation cooling systems in a retail space. The BigHorn Center is the first commercial building in the State of Colorado to have standing-seam metal roof-integrated PV systems. The Phase III PV system is the largest building-integrated PV system in Colorado. The BigHorn Center is also one of the first net-metered commercial buildings in Colorado.

The National Renewable Energy Laboratory (NREL) High-Performance Buildings Research project took an interest in the BigHorn Center because the owner was committed to integrating aggressive daylighting and other efficiency features into the building design. The owner believes daylighting, energy-efficient, and renewable-energy design strategies will reduce the impact on the environment and improve sales. Researchers at NREL facilitated the holistic approach to the BigHorn Center design and performed simulation-based optimization studies that determined how best to integrate energy efficient and renewable energy technologies. NREL also provided the metrics to measure the progress and success of the project. (NREL 2000; Torcellini, Hayter & Judkoff 1999)

Phase III Building Analysis

The BigHorn Center is located in Silverthorne, Colorado, at an elevation of 9,065 ft and with 10,803 (base 65°F) Heating Degree-Days (NREL 1999). The Phase III building includes a 12,000-ft^2 retail space (hardware store), 3000 ft^2 of offices and support areas, and a 22,000 ft^2 building materials warehouse. Both the retail space and warehouse are single story with an approximately 35^o-angled sloped roof. The interiors have open floor plans and no attic.

Base-Case Analysis

The impact of all design decisions on the building energy performance was analyzed using an hourly building-energy simulation tool (LBNL 1994). A base-case model was created to which design improvements were compared. The base-case model has the same footprint area as the as-built building. It is solar neutral (equal glazing areas on all orientations) and meets the minimum requirements of the Federal Energy Code 10CFR435 (based on ASHRAE Standard 90.1-1989 with additional lighting requirements) (ASHRAE 1989; USGVMT 1995). Infiltration in the base-case model was set at a constant rate: 0.5 air changes per hour (ACH) during occupied periods and 0.3 ACH during unoccupied periods. As with most current retail operations, no daylighting was assumed in the base-case model and electric lights provided all lighting. During occupied periods, the lighting was set at 2.32 W/ft^2, 1.34 W/ft^2, and 0.42 W/ft^2 in the retail, office, and warehouse areas, respectively. Occupancy schedules were based on typical operation hours from an actual hardware store. The owner provided expected customer density data to establish the air-exchange rates. Table 1 summarizes the building characteristics in the base-case model.

Table 1. Base-Case Model Characteristics

Item	Value
Wall R-Value (ft·°F·hr/Btu)	16
Window U-Value(Btu/ft·°F·hr)	0.32
Window Shading Coefficient	0.69
Floor Perimeter Insulation R-Value (ft·°F·hr/Btu)	13
Roof R-Value (ft·°F·hr/Btu)	23

Conventional retail building construction characteristics vary so it is difficult to justify base-case model characteristics that do not conform to a universally accepted standard set of criteria. ASHRAE Standard 90.1-1989 is a consensus-based standard that outlines the minimum building energy design requirements. The Federal Energy Code 10CFR435 adopted this industry standard in its entirety and incorporated additional lighting requirements. Many states and municipalities do not require or do not strictly enforce Standard 90.1 or 10CFR435 requirements. Therefore, a building designed to meet 10CFR435 is often a better building than conventional construction. For these reasons, the estimated savings reported in this paper are probably better than those anticipated compared to 10CFR435.

The base-case model's primary loads are to operate the heating, fan, and lighting systems (Figure 6). The base-case model represents a typical retail space that meets consensus based energy codes; it does not take advantage of daylighting and uses conventional heating and cooling systems. The climate in Silverthorne, Colorado is a heating-dominated climate. As a result, buildings in this climate typically experience large fan energy requirements to provide ventilation and move heated air (heating in most Silverthorne retail spaces is provided by distributing heated air). Buildings in this climate experience cooling loads as well. Typically, solar and internal gains dominate cooling loads. As a result, cooling systems are installed to remove these loads. Elimination of these loads results in a building needing little or no air conditioning.

Daylighting Design

The largest energy savings result from using daylight to meet most of the lighting loads. The focus of the envelope design was to maximize the daylighting potential while balancing the heating and cooling requirements. It is estimated that daylighting will reduce the lighting load by 79% compared to the base-case model. Figure 2 shows daylighting on an overcast day in the retail space during construction.

Figure 2. Daylighting in the Retail Space

Glazing design in the hardware store. Daylighting enters the space from several locations. Diffuse daylight enters through equally spaced dormer windows along the north edge of the store and through north-facing clerestory windows. South-facing clerestory windows with engineered overhangs provide the majority of the lighting for the space. East-and west-facing windows provide a limited amount of direct-beam sunlight to the front and back of the building. Limited west-facing windows provide daylighting to the contractor service area and a view of the warehouse yard. Direct-beam sunlight through these west windows could cause glare problems in the contractor area. However, the owner felt it was more important that employees have an unobstructed view of the warehouse yard than to address the glare issue. Storefront windows and glass doors at the occupant level are located on the building's east wall. A roof above this glazing extends horizontally 10 ft. Mountains located to the east of the BigHorn Center minimize direct-beam sunlight through the storefront glazing early in the morning and the roof shades the glazing later in the morning. Minimizing direct-beam sunlight and ensuring diffuse daylight in the space reduces glare on the store product and employee work surfaces.

Distribution of daylighting is improved by painting the ceilings and walls white. The floor tiles in the retail space are also white. It is important that these surfaces are bright so that they do not absorb the daylight.

Burgundy trim was used in the office areas to provide warmth and contrast to these spaces and to improve the quality of the daylighting. Limited direct-beam sunlight is used to highlight areas and provide a "sense of time." Daylighting without some direct-beam sunlight and contrast tends to make colors appear flat, which often results in occupant desire to turn on electric lights to add "sparkle" to the environment (Torcellini & Wood 2000).

Interior windows into offices and other enclosed areas allow shared light to enter these spaces, further reducing the need for electrical lighting.

Glazing design in the warehouse. Large insulated diffusing skylights located along the ridgeline provide daylighting to the warehouse. These skylights are translucent fiberglass sheets that sandwich a grid core constructed of interlocked I-beams. The core is filled with colorless spun fiberglass. This construction diffuses the daylight and provides a high rated U-value (Kalwall 1999).

Skylights were chosen over clerestories because clerestories on the warehouse would have exceeded local building code height restrictions. The function of the warehouse is completely different than the retail space. Providing daylight to the center of the warehouse was a more important design requirement than avoiding solar gains. Also, because the Silverthorne, Colorado summer climate is cool and dry, summer solar gains through the skylights are acceptable. In this particular case, the best design solution was to use skylights; however, it should be noted that this might not be the best solution in all climates and for all building types. Distribution of daylighting is improved by painting the warehouse ceilings and walls white. The bright surfaces help reflect the daylighting within the space (Figure 3).

Daylighting system control in the hardware store. The electric lighting fixtures in the hardware store each contain eight 26-W, compact fluorescent lamps grouped within a domed glass shade. Pairs of lamps are controlled together (four pairs per fixture) to allow four levels of lighting from each fixture. A stepped lighting control was selected over continuous dimming control because of lower capital cost. The lights are controlled by the energy management system (EMS), which also controls other building mechanical and electrical systems. Required lighting levels are based on store operating schedules. An override is available for off-hours occupancy. Motion sensors control the lighting in the interior offices, employee break room and restrooms.

Figure 3. Daylighting in the Warehouse

The light fixture placement complements the daylighting design – fixtures are located in rows parallel to the clerestory. The zoning for the lighting was established by observing lighting levels with various combinations of lamps on during a sunny afternoon/evening. Eight "lighting patterns" were identified and hard-wired. When all eight zones of lights are on, the lighting density in the hardware store is 1.21 W/ft^2.

Daylighting system control in the warehouse. The lighting fixtures in the warehouse are the same fixtures that are found in the hardware store. Similar to the hardware store, the warehouse lighting fixtures are controlled in eight separate zones. The fixtures are located in rows parallel to the skylights. In all enclosed areas (e.g., employee break room, and mechanical room), separate photo/occupancy sensors automatically turn on the lights when there is insufficient daylight and there is detected motion in the space. The installed lighting density in the warehouse is 0.42 W/ft^2.

Daylighting system performance. There are two categories for evaluating lighting system energy savings – the electric lighting design and the daylighting design. In the BigHorn Center, the electric lighting design, including fixture selection, interior décor colors, and fixture layout, uses 39% less energy than a code-compliant building. Table 2 compares the installed lighting power densities in the base-case model and the as-built design.

The daylighting design (the second category) is expected to save about 65% on an annual basis, as is shown in Figure 4. This figure shows the simulated as-built design with and without daylighting. Combining both electric lighting and daylighting design savings results in an overall expected lighting energy savings of 79%.

Table 2. Lighting Power Density Comparison between the Base-Case Model and As-Built Design

Location	Base-Case (W/ft^2)	As-Built (W/ft^2)
Retail store	2.32	1.21
Warehouse	0.42	0.42
Offices	1.34	1.21

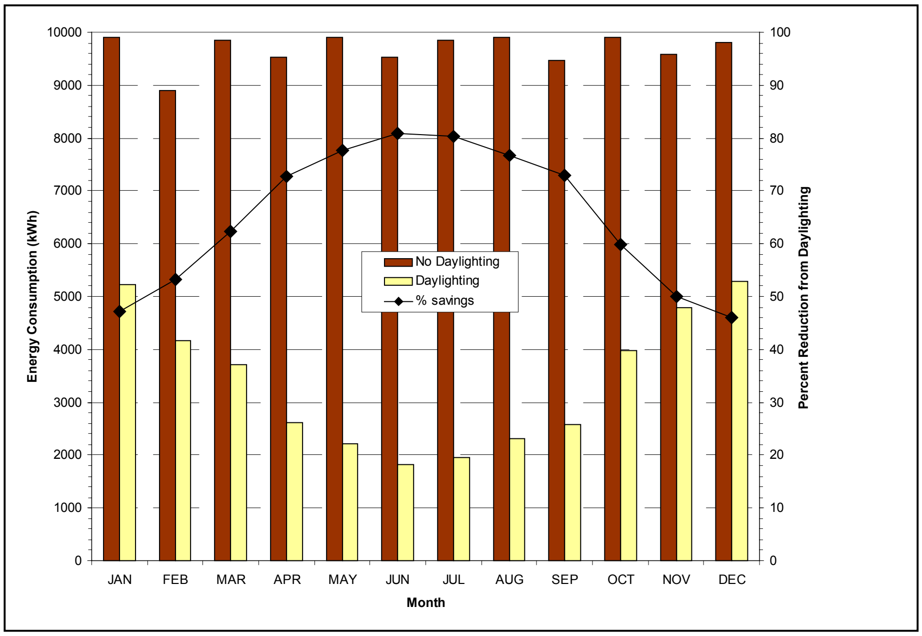

Figure 4. Comparison of Annual Monthly Energy Consumption of Daylighting versus no Daylighting in the As-built Design

The anticipated lighting energy savings vary from 46% in the winter to 81% in the summer. The most significant decrease in lighting energy consumption occurs between April and September, when the days are longer. Decreasing lighting loads during these months have the added benefit of also reducing the internal gains during the time of year when the cooling loads are the highest. The elimination of the cooling system was a direct result of minimizing the lighting loads and the summer solar gains. Reduced cooling loads make it possible to meet the cooling requirements with natural ventilation, discussed later in this paper.

Mechanical and Electrical System

Hardware store mechanical system. A hot-water radiant floor heating system provides heating in the retail space. The system is divided into ten zones to give flexibility in controlling the amount of heat supplied to various parts of the space. For example, more heat will be provided to areas where employees will be located for long periods of time, such as the cash register area.

The summer cooling loads in the hardware store are expected to be low. Natural ventilation will offset these loads. Air drawn through open doors in both the front and back of the store will rise because of the stack effect and exit through the opened north-facing clerestory windows.

Thermostatically-controlled ceiling fans will reduce temperature stratification in the space. The even indoor temperature throughout the space will help improve comfort.

Warehouse mechanical system. Two separate systems provide heating in the warehouse. A transpired solar collector heats ventilation air and overhead gas-fired radiant heaters meet remaining heating loads that cannot be met by the transpired solar collector system. Customers are allowed to drive vehicles into the warehouse to load product, which results in a high ventilation requirement for the warehouse. The ventilation load combined with the long heating season in Silverthorne, Colorado make the warehouse a good candidate for a transpired solar collector system (Conserval 2000). The indoor temperature in the warehouse will be maintained at an effective temperature of 50°F.

Building-integrated photovoltaic system. Figure 5 shows the BigHorn Center Phase III roof-integrated photovoltaic (PV) system. Photovoltaic modules laminated onto the standing-seam metal roof panels were installed on the south-facing roofs of the hardware store clerestory and the warehouse center dormer (Ovonic 2000). The amphorous-silicon PV modules were wired into three arrays, each serving one phase of the 3-phase building power system. The design capacity of the PV system is 8 kW. The BigHorn Center owner has a net metering agreement with the local utility to receive full credit for power that the PV system exports back to the grid.

Figure 5. Installation of the Photovoltaic Roof

Energy management system. An energy management system optimized operation of the mechanical and lighting systems in the retail store. The system controls the heating system setback, operates the automatic window actuators for the north-facing clerestory windows, operates the ceiling fans, and balances daylighting and electric lighting to maintain constant lighting levels in the space. According to computer simulation results, the energy features coupled with the energy management system are expected to reduce energy costs by 62%, compared to the base-case model (Figure 6).

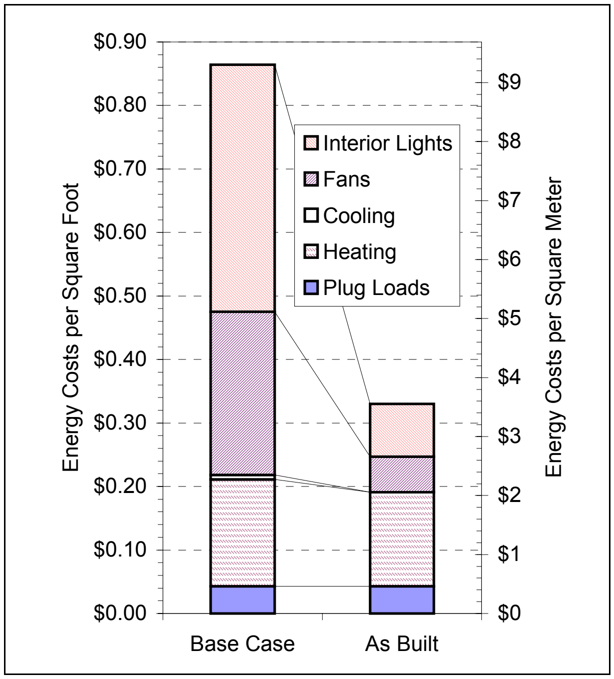

Figure 6. Comparison of Base-Case Model and As-Built Design Annual Energy Costs

Building Envelope

The building envelope was optimized to minimize heat loss/gain and infiltration. Extruded polystyrene insulation was installed on the outside of the steel stud walls to minimize thermal bridging. Fiberglass batt insulation is located between the studs. Insulation was installed under the entire hardware store slab and surrounding the stem walls. The warehouse has only stem wall insulation. All glazing was specified to be double-pane with a low-e coating. Table 3 summarizes the envelope characteristics in the as-built design.

Table 3. As-Built Design Characteristics

Item	Value
Wall R-Value (ft·°F·hr/Btu)	15
Window U-Value(Btu/ft·°F·hr) for the Clerestory/All Other Windows	0.3/0.24
Window Shading Coefficient for the Clerestory/All Other Windows	0.86/0.50
Floor Slab Insulation (entire slab) R-Value (ft·°F·hr/Btu)	10
Roof R-Value (ft·°F·hr/Btu)	38

Construction/Operating Costs

The BigHorn Center owner financed the entire project using conventional financing means. The additional cost for features such as the building-integrated PV system and the advanced control system were included in the overall cost of the building when a loan was authorized for the building construction. There were no incentives, rebates, or other non-conventional financing methods available to offset the construction costs. The owner anticipates an acceptable life-cycle cost for his investment because of the combined effect of decreased operating expenses plus the increased sales he expects to obtain. The increased sales will result from marketing the sustainable features of the building and offering a more pleasant shopping experience in the daylit store. A detailed cost analysis of the project will be completed in the future.

It is important to note that the energy efficiency technologies were evaluated as a single package. Each piece of the design interacts with the others to create a low-energy building. The entire package was cost-effective from a business plan point of view. Attributes related to the image of the sustainability had real value in the business plan, but may not be "cost-effective" in the traditional sense.

Summary

The owner of this project made a strong commitment to sustainable design practices. The business plan for the project encompassed the ability to sell "green" products in the retail environment. To that end, the BigHorn Center became a statement to the sustainable mission and the energy features were an integral part in the building design. Additional cost was incurred for the PV integrated into the roofing; however, the marketing value of this investment, coupled with the other features, created a total cost effective business plan.

The most influential member of the design team to spearhead sustainable building design goals was the owner. He initiated the idea to incorporate energy-efficient and renewable-energy technologies into the design and he encouraged the architect to pursue these goals. He researched sustainable design strategies and sought advice from building energy and renewable energy systems experts. This owner was committed to minimizing the impact his buildings have on the environment.

The design team used a whole-building design approach to integrate improved daylighting opportunities, efficient mechanical systems, and improved envelope features into an optimized design. A base-case model was created at the onset of the design process to set a metric against which to compare the impact of all design decisions. It is estimated that the BigHorn Center Phase III design saves approximately 21 kW in demand, making it possible for the 8 kW of PV power to meet a significant portion of the annual building electrical load. If daylighting and other design features had not been incorporated, it would not have been feasible to purchase and install enough PV power to offset an equivalent portion of the base-case model load.

Improving the lighting system design and incorporating daylighting provided the greatest opportunities to reduce energy costs. Optimizing the envelope design and implementing efficient lighting fixtures and daylighting controls is expected to reduce the building lighting loads by an estimated 79%. The anticipated energy cost savings resulting from the combined effect of all the features discussed in this paper (not including the PV system contributions) is 62%.

The results presented in this paper are based on computer simulations. Actual building energy performance is currently being monitored. The collected data will be used to verify the anticipated results.

Acknowledgements

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Marketplace Architects in Dillon, Colorado completed the architectural design. Tolin Mechanical of Silverthorne, Colorado, was the controls contractor. The building-integrated PV design was completed by Burdick Technologies Unlimited of Lakewood, Colorado, and the SolarWall system was designed by Foltz Engineering in Estes Park, Colorado.

References

[ASHRAE] American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1989. *ASHRAE Standard 90.1-1989*. Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Conserval. 2000. *Solarwall* Web Site. www.solarwall.com.

Kalwall. 2000. *Kalwall* Web Site. www.kalwall.com.

[LBNL] Lawrence Berkeley National Laboratory and Hirsch and Associates. 1994. *DOE-2 version 2.1e*. Berkeley, Calif.: Lawrence Berkeley National Laboratory.

[NREL] National Renewable Energy Laboratory, 1999. *Designing and Constructing Low-Energy Buildings: Passive Solar Strategies and Energy-10 Software 1.3.* Golden, Colo.: National Renewable Energy Laboratory.

[NREL] National Renewable Energy Laboratory. 2000. *High Performance Buildings* Web Site, www.nrel.gov/buildings/highperformance. Golden, Colo.: National Renewable Energy Laboratory.

Ovonic. 2000. *UniSolar* Web Site, www.ovonic.com/unisolar.

Torcellini, P.A., S.J. Hayter, and R. Judkoff. 1999. "Low-Energy Building Design - the Process and a Case Study," In *ASHRAE Transactions, V 105, Part 2*. 802-810. Atlanta, Ga.: American Society of Heating Refrigerating and Air-Conditioning Engineers.

Torcellini, P.A., and T.R. Wood. 2000. *Daylighting Analysis in the Solar Energy Research Facility*. NREL/TP-550-27700. Golden, Colo.: National Renewable Energy Laboratory.

[UNCED] United Nations Conference on Environment and Development. 1992. *Agenda 21: Programme of Action for Sustainable Development*. New York: United Nations.

[USGVMT] Office of the Federal Register National Archives and Records Administration. 1995. *Code of Federal Regulations 10 - Energy*. Washington, D.C.: Office of the Federal Register National Archives and Records Administration.

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13. ABSTRACT *(Maximum 200 words)*
This paper focuses on implementation of daylighting into the BigHorn Center, a collection of home improvement retail spaces in Silverthorne, Colorado, which were constructed in three phases. Daylighting was an integral part of the design of the Phase III building. Energy consultants optimized the daylighting design through detailed modeling using an hourly building energy simulation tool. Energy consultants also used this tool to address the building owner's concerns related to customer comfort and increased product sales.

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